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A search on the source composition of primary cosmic nuclei of Z ≤ 28 from Alice Spring results

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Abstract : A study has been made on the elemental abundance of primary cosmic rays over Alice Springs obtained from the 32 hour exposed balloon borne plastic-emulsion chamber experiment The long hour etched CR39 (doped with HCB 0.5%) nuclear track detector exhibit 3298 etch pits whose measured diameter distribution yields a cosmic charge abundance in the range Z ~ 10–28 The observed charge spectrum has been corrected to account for the loss of nuclei fluxes due to interactions and fragmentation during the time of propagation of cosmic nuclei in the Galaxy by using the standard diffusion equation with fitted partial cross-sections of Wilson *et al* The estimated charge spectrum has been used to explore source composition of primary cosmic nuclei by adopting the Steady State Leaky Box model

Keywords Nuclear abundance, balloon borne plastic emulsion chamber, galactic propagation

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1. Introduction

The study of chemical composition of primary cosmic rays is of astrophysical importance because, the charge composition of cosmic ray nuclei in stratosphere can predict the pattern of source composition in the Inter Stellar Medium.

The present investigation is based on a 32 hour balloon exposure data over Alice Springs, Australia, where CR-39 (HCB 0.5%) solid state nuclear track detector (SSNTD) has been used along with Fuji ET-7B nuclear emulsion. This type of CR39 polymer made by Teijin Lens Ltd., Japan has also been used earlier by Tasaka *et al.* [1] and Sato *et al* [2] for the estimation of integral flux of very heavy (VH) nuclei above 4.1 GeV/n energies. The present location of flight has a cut-off rigidity for proton which is 9.34 GV that yield the cut-off energy

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of Fe nuclei to be 4.1 GeV/n. The amount of radiation damage caused by a particle of particular (Z/β) is the response parameter of the detector and is called the reduced etch rate s = $V_T/V_G - 1$, where V_T is the velocity of chemical etching along the track and V_G is the general velocity of etching in the polymer. During the chemical treatment the detector material is etched out along the particle track forming a 3-dimensional cone shaped pit due to the above mentioned two different etch rates. The surface openings of those pits are elliptic or circular depending on the angle of incidence of the corresponding incoming particle. From the geometry of these pits the response parameter s can be calculated.

The present work is concerned with the estimation of chemical composition of primary cosmic rays over Alice Springs using CR39 (HCB) and emulsion (Fuji ET-7B) stack which have been exposed on board of a balloon for 32 hours at an atmospheric depth of 9.8 g-cm^{-2}. We have estimated the source composition of primary cosmic nuclei using Steady State Leaky Box model fitted with the partial cross-sections for Fe+H interactions obtained from the code of Wilson *et al.* [3] which is based on their theoretical "abrasion-ablation model" for high energy heavy ion interaction. We have compared the present source composition with the similar results obtained from SSLB model fitted with the partial cross-sections expected from the semi-empirical formulation of Tsao *et al.* [4].

2. The experiment

CR-39 (HCB 0.5%) plastic and Fuji ET-7B nuclear emulsion of detector area (50 × 40) cm^2 and of weight 120 kg has been exposed for 32 hours on board balloon over Alice Springs, Australia (Lat. 23^{0}49', Long. 133^{o}53' E) in 1983. The average level of flight was 9.8 g-cm^2. After exposure the recovered plates are chemically processed. Some of the CR39 (HCB 0.5%) plates from the top stack were etched in 7.5 N NaOH solution at (80 ± 0.1)^{o}C for 96 hours. The estimated bulk etch rate of this intense etching was 4.95 μm/h. Such type of etching yields sufficiently large etch pits which enables one to scan faster and reduces experimental error. Total 414 cm^2 area has been scanned, which registered 3298 etch pits of very heavy cosmic ray particles. The calculated geometric factor of the plastic emulsion chamber was (π/2.3)sr. The time of flight was 32 hour which yields the solid angle-time-area factor of value 6486.22 m^{2}s sr.

3. Results and discussion

The plastic stack registered 3298 very heavy ion tracks within the scanned area of 0.04 m^2. After etching the tracks are developed as elliptic pits visible optically under a microscope. The major axis (D_A) and minor axis (D_B) of the etch pits are measured under a Leitz Ortholux optical microscope with a total magnification of × 120. From the measured parameters the charge response V_T/V_G of the detector has been estimated using the formulation of the detector has been estimated using the formulation of Henke and Benton [5] as follows

$$s = \cdot \quad 1 + \cdot \frac{4(D_A/2H)^2}{\left\{1-(D_B/2H)^2\right\}^2} \tag{1}$$

The identified charges are also confirmed by the δ-ray counting of the corresponding tracks recorded in the adjacent emulsion sheet.

(a) Cosmic ray composition at the top of the atmosphere :

We have taken the observed cosmic ray elemental fluxes of Ne(Z = 10) to Ni (Z = 28) from our analysis and duly corrected those fluxes for interactions and fragmentation in the 9.8 g-cm^{-2} of residual atmosphere present. The spallation cross-section used in this correction is taken from the computer code based on the theoretical Abrasion-Ablation model of Wilson *et al.* [3]. Nitrogen is taken as the target nucleus equivalent to air in this computer code. The corrected flux is estimated numerically by solving a set of 19 (for each of the Z = 10 to 28 nuclei) diffusion equations of cosmic ray propagation, which can be written in a generalised form as follows

$$\frac{dN_i(E)}{dx} = \frac{\sigma_i N_i(x)}{m} + \Sigma_{j>i} \frac{\sigma_{ji} N_j(x)}{m} . \tag{2}$$

where $N_i(x)$ is the flux of the i-th element at a depth x, σ_i is the total charge-changing cross-section for the element i, σ_{ji} is the partial cross-section of the j-th element fragmented to the i-th taken from Wilson *et al* [3] and m is the mass of the target media (atmosphere). The total interaction cross-section σ_i is taken according to Binns *et al.* [6] as

$$\sigma_i = 10\pi\,(1.35)^2 \left[A_T^{1/3} + A_B^{1/3} - p(A_T + A_B)^q\right]^2 , \tag{3}$$

where A_T and A_B are the target and beam masses respectively, p = 0.209 and q = 0.332, and A_T = 14.08 taken for atmosphere.

The nuclear abundance at the top of the atmosphere as obtained after atmospheric correction using the partial cross-section after Wilson *et al.* [3] is shown in Table-1 along with those obtained using the partial cross-section of Tsao *et al* [4]. The sub-iron group abundances are lowered with the partial cross-section of Wilson *et al* [3], but those of Si-group show no significant change.

(b) Cosmic ray composition at source :

The corrected elemental abundances at the top of the atmosphere are also affected by the spallation of the cosmic rays during their traversal from their source to Earth through the interstellar medium (ISM). To estimate the abundance of primary nuclei before propagation through the ISM which is named as source abundance here, we have adopted the Steady State Leaky Box (SSLB) model [7-9]. The propagation equations can be written in the form

$$\frac{\delta N_i}{\delta x} = 0 = Q_i + <X> \Sigma_{j>i} \frac{N_j}{\lambda_{ji}} - <X> N_i \left(\frac{1}{\lambda_i} + \frac{1}{\lambda_{esc}}\right), \tag{4}$$

where Q_i is the source term generating i-particles cm^{-3} s^{-1} in the galaxy, N_i and N_j are the density of the species i and j, λ_{ji} is the interaction path length of the species j (> i) for fragmenting into species i, λ_i is the interaction path length for species i in ISM. In the present calculation, the ISM is assumed to be composed solely of hydrogen. The average of the column density <X> has been calculated using the relation

$$<X> = m_p \bar{n}\, \beta ct , \tag{5}$$

where m_p is the proton mass = 1.67 × 10^{-24} gm, n is the average interstellar density taken as 0.3 atom per cm^{-3}, β = 0.987, t_{Fe} = 2.1 × 10^{6}y is the life time of Fe taken from the survey of Allkofer

[10]. The life time t_A is related to the projectile elemental mass number by the relation

$$t_A = 4.1435 A^{0.856551} \times 10^7 \text{ y}. \tag{6}$$

The above form of the mass number dependence is obtained after normalizing the lifetime with that of Be using the results of Shapiro *et al.* [11]. The column density is found to be 0.98.

For the calculation of partial cross-sections ($1/\lambda_{il}$) for cosmic nuclei + H interactions we have used a computer code developed by Wilson *et al.* [3]. The interaction mean free path $1/\lambda_i$ is again derived from eq. (3) with A_T = 1.008 for the ISM. The escape path length λ_{esc} is taken to be 5 g-cm^{-2} from the rigidity dependence formulation of Ormes and Frier [9] as follows,

$$\lambda_{esc} = 5.5\left[\frac{7.6GV}{R}\right]^{0.4} \text{g-cm} \tag{7}$$

Table 1. Table shows the observed fluxes in arbitrary units and the corrected fluxes along with their source composition

Element	Charge Z	Observed no of events	Corrected no of events	Source composition
Ne	10	609	822	1241
Na	11	104	30	0
Mg	12	774	1166	1919
Al	13	139	154	201
Si	14	624	1006	1750
P	15	41	28	3
S	16	132	190	300
Cl	17	41	28	0
Ar	18	70	89	116
K	19	42	39	21
Ca	20	80	109	149
Sc	21	35	26	0
Ti	22	47	52	27
V	23	39	32	0
Cr	24	62	75	58
Mn	25	58	56	6
Fe	26	382	751	1562
Co	27	3	6	9
Ni	28	16	32	68

The sub-Fe/Fe flux ratio at source derived from SSLB model using the nuclei + H fragmentation cross-section of Wilson *et al.* [3] are displayed in Table-2 along with those obtained using the fragmentation cross-section from Tsao *et al.* [4].

The Table 2 exhibits that the our derived sub-Fe/Fe flux ratio results are of much lower value when compared to that found earlier by Protheroe *et al.* [12], Margolis and Bussard [13] but is in well agreement with the results of Soutoul *et al.* [14].

Table 2. Comparative study of sub-Fe to Fe flux ratio expected from different experiments

Elemental flux ratio at the top of the atmosphere	Present Expt. with Wilson *et al.* [3]	Present Expt with Tsao *et al* [4]	Protheroe *et al* [12]	Margolis *et al* [13]	Soutoul *et al* [14]
(Sc-Cr)/Fe	0 2463	0 285	0 390	-	0 34
(Sc-Mn)/Fe	0 3209	0 342	0 490	0 480	–

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